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Aeronautical Mobile Airport Communications System (AeroMACS)

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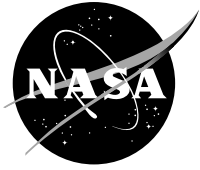
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1.0   Introduction

To help increase the capacity and efficiency of the nation's airports, a secure wideband wireless communications system is proposed for use on the airport surface. This paper provides an overview of the research and development process for the Aeronautical Mobile Airport Communications System (AeroMACS). AeroMACS is based on a specific commercial profile of the Institute of Electrical and Electronics Engineers (IEEE) 802.16 standard known as Wireless Worldwide Interoperability for Microwave Access or WiMAX (WiMax Forum). The paper includes background on the need for global interoperability in air/ground data communications, describes potential AeroMACS applications, addresses allocated frequency spectrum constraints, summarizes the international standardization process, and provides findings and recommendations from the world's first AeroMACS prototype implemented in Cleveland, Ohio, USA.

1.1   Future Communications for Next Generation Air Transportation

The highest concentration of sources, users, and stakeholders of information required for safe and regular flight operations occurs at the nation's airports. Of all flight domains within the national airspace system (NAS), the airport domain is the one where aircraft are in closest proximity to each other and to a wide variety of service and operational support vehicles, personnel, and infrastructure. Air traffic controllers, aircraft pilots, airline operators, ramp operators, aircraft service providers, and security, emergency, construction, snow removal, and deicing personnel all contribute to the safe and efficient operation of flights.

As the communications, navigation, and surveillance (CNS) facilities for air traffic management (ATM) at an airport grow in number and complexity, the need for communications network connectivity and data capacity increases. Over time, CNS infrastructure ages and requires more extensive and expensive monitoring, maintenance, repair or replacement. Airport construction and unexpected equipment outages also require temporary communications alternatives. Some typical examples of airport infrastructure, aircraft, service vehicles, and operators are shown in Figure 1.

Capacity growth in the nation's airports helps increase the total capacity of the NAS. But how can that growth occur while maintaining required safety, security, reliability, and diversity? A high-performance, cost-effective wireless communications network on the airport surface can provide part of the solution.

Through collaboration with the United States (U.S.), the Federal Aviation Administration (FAA) Headquarters in Washington, DC, the National Aeronautics and Space Administration (NASA) Glenn Research Center (Glenn) in Cleveland, Ohio, and its contractor, the ITT Corporation (ITT) in Fort Wayne, Indiana, are developing AeroMACS. AeroMACS is the first of three elements of the proposed future communications infrastructure (FCI)—a harmonization of future aeronautical air-to-ground (A/G) data communications capabilities intended to support the shared visions of the FAA's Next Generation (NextGen) Air Transportation System in the U.S. (FAA, 2011) and Europe's Single European Sky ATM Research (SESAR) program (SESAR, 2011).

Figure 1.—Examples of typical airport infrastructure, aircraft, service vehicles, and operators that benefit from improved communications.

AeroMACS offers the potential for transformational broadband secure wireless mobile data communications capabilities to future air traffic controllers, pilots, airlines, and airport operators on the airport surface. The unprecedented connectivity, bandwidth, and security afforded by AeroMACS have the potential to greatly enhance the safety and regularity of flight operations in the future.

2.0   Call for Global Harmonization

This section describes the steps that led to joint recommendations between the U.S. and Europe for a future wireless communications network on the airport surface. In the early 2000s, the International Civil Aviation Organization (ICAO) Aeronautical Communications Panel (ACP) recognized that the very high frequency (VHF) band allocated globally for A/G voice and data communications for ATM was beginning to reach saturation. The problem was characterized at the time as being more severe in Europe than in the U.S. However, both had taken steps to significantly reduce VHF channel spacing (from 50 to 25 kHz in the U.S. and from 25 to 8.33 kHz in Europe). This reduction allows more simultaneous voice and data services in the crowded VHF spectrum. Various proposals for digital A/G datalinks from individual countries obtained ICAO approval independently. But none achieved global endorsement.

The call to action came from ICAO's Eleventh Air Navigation Conference (ANC-11) held in Montréal, Quebec, Canada in late 2003. ANC-11 advanced the operational concept of global ATM as guidance for the development of future ATM-related service provisions through the year 2025 and beyond. The official report of the "Technical and Operational Matters in Air Traffic Control Committee" included several observations regarding the state of global aviation communications (ICAO ANC, 2003). Those included the need for the aeronautical mobile communications infrastructure to evolve in order to accommodate new functions, the gradual introduction of data communications to complement and eventually to replace voice for routine communications, and the universally recognized benefits of harmonization and global interoperability of A/G communications.

The committee made specific recommendations to develop an evolutionary approach for global interoperability of A/G communications (Recommendation 7/3), conduct an investigation of future technology alternatives (Recommendation 7/4), and prove compliance with certain minimum criteria before undertaking future standardization of aeronautical communications systems (Recommendation 7/5).

2.1   Future Communications Study

These recommendations helped establish the goals for the Future Communications Study (FCS), a joint investigation by the FAA and EUROCONTROL also referred to as Action Plan 17 (AP-17) under the Memorandum of Cooperation between the two organizations. AP-17 was approved in early 2004 and modified over the course of the 4-year FCS (Fistas et al., 2007). Under the FCS, the Communications Operating Concepts and Requirements (COCR) for future A/G data communications was developed jointly and revised once (version 2.0) (ICAO COCR, 2007). The COCR provides the shared vision for future ATM concepts of operations and services in all flight domains. Two phases of development were considered.

The first phase (roughly 2005 through 2020) envisions increased use of data communications, but within the current tactical aircraft management practices at the time. The concepts identified in the second phase (roughly 2020 and beyond) anticipate a paradigm shift towards ATM based primarily on data communications in all flight domains, with use of voice intervention by exception. The COCR served as the basis for selecting technologies for the future radio system (FRS), the A/G portion of the overall FCI. The FCS technology assessment directly implemented a key recommendation of ANC-11.

Recommendation 7/4—Investigation of future technology alternatives for air-ground communications: *That ICAO*

a) *investigate new terrestrial and satellite-based technologies, on the basis of their potential for ICAO standardization for aeronautical mobile communications use, taking into account the safety-critical standards of aviation and the associated cost issues;*
b) *continue evolutionary development of existing standardized ICAO technologies with a view to increasing their efficiency and performance; and*
c) *assess the needs for additional aeronautical spectrum to meet requirements for increased communications capacity and new applications, and assist States in securing appropriate additional allocations by the ITU* (ICAO ANC, 2003).

2.2   Common Recommendations for Future Communications Infrastructure

Beginning in 2004, NASA Glenn and its contractor, ITT, conducted the FCS technology assessment for the U.S., evaluating the technical and operational capabilities of over 60 different commercial, public safety, and Government communications services and standards for applicability to the COCR. The U.S. technology assessment was conducted in close cooperation with EUROCONTROL and their contractor, QinetiQ. The process was conducted in multiple phases. The first of these, technology pre-screening, provided an initial down-selection against detailed functional and performance evaluation criteria. The second phase included detailed investigations of a smaller set of candidates. Simulation and evaluation in the third phase led to a harmonized shortlist of common recommendations. The process is illustrated in Figure 2 (Gilbert et al., 2008).

The international harmonization process was carried out over multiple meetings of ICAO's Aeronautical Communications Panel (ACP) Communications Working Groups (WGC-8 through WGC-11) and Working Group Technology (WGT) to establish common solutions for future A/G data communications in the 2020 timeframe (ICAO WGC, 2006) (Phillips et al., 2007). An underlying objective of the FCS technology assessment was to maximize existing technologies and standards and minimize any modifications to each. This approach leverages existing commercial industry resources invested in developing and standardizing the technology and can expedite ICAO approval as an international aviation standard.
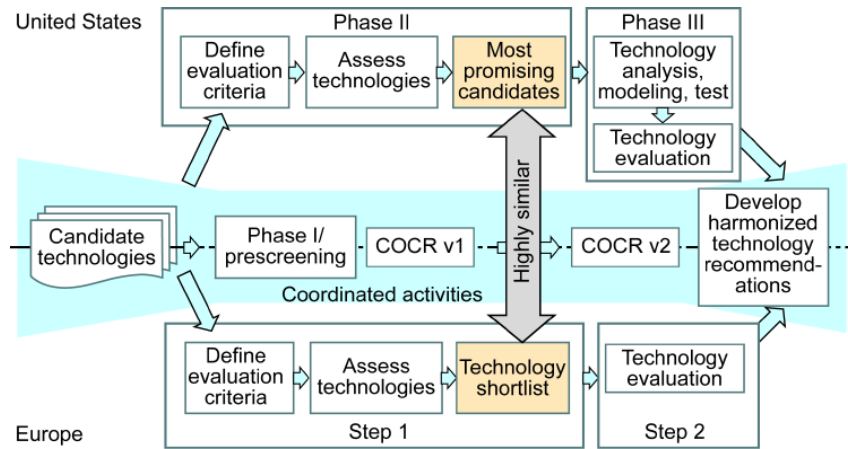
Figure 2.—The technology assessment process used in the Future
Communications Study.

Figure 3.—The common technology recommendations of the Future
Communications Study.

The FCS technology assessment considered technology candidates as elements of FCI in three flight domains—continental (i.e., enroute airspace within line of sight of terrestrial air traffic control (ATC) communications facilities), oceanic and remote airspaces (i.e., enroute airspace beyond line of sight of terrestrial facilities), and airport (i.e., pre-departure and post-arrival on the surface). The common shortlist of technologies recommended for further evaluation through prototype developments was approved by ACP in April 2008 at the Second Working Group of the Whole (WGW-2) and is summarized in Figure 3 (ICAO WGW, 2008). Gilbert et al., 2006 provides details regarding evaluation of IEEE 802.16e for the airport surface.

The common recommendation to be used as the starting point for aeronautical wireless mobile data communications on the airport surface was the 2005 version of the IEEE standard for local and metropolitan area networks, IEEE 802.16e. AeroMACS, the first element of the FCI, is based on the most current version of this standard, IEEE 802.16-2009, Part 16: Air Interface for Broadband Wireless Access Systems (IEEE, 2009).

Throughout this paper, the term "IEEE 802.16" will refer to the 2009 version of that standard. The evolving standard is well suited for implementation below 11 GHz. The amendment for mobility uses 512 subcarrier (in 5-MHz channel) orthogonal frequency division multiple access (OFDMA) modulation and supports multiple channel bandwidths from 1.25- to 20-MHz, with peak duplex data rates above 50 Mbps. Table 1 highlights some features of the IEEE 802.16 mobile standard that makes it attractive for use on the airport surface.

TABLE 1.—FEATURES OF IEEE 802.16 DESIRABLE FOR IMPLEMENTATION OF AeroMACS NETWORKS

Feature	Advantages
Mobility	Supports vehicle speeds of up to 120 km/hr , sufficient for aircraft taxiing and emergency surface vehicle speeds
Range	Covers up to ~10 km in line-of-sight (LOS) communications, sufficient to cover most airports
Link Obstruction Tolerance	Exploits multipath to enable non line-of-site (NLOS) communications
Quality of Service (QoS)	Enables QoS based on throughput rate, packet error rate deletion, scheduling, time delay and jitter, resource management
Scalability	Includes flexible bandwidth and channelization options to enables network growth on demand
Security	Includes mechanisms for authentication, authorization, strong encryption, digital certificates, and fast handovers
Privacy	Supports private Virtual Local Area Networks (VLANs)
Open Sourced	Leverages modern communications technologies and supports modern Internet-based network protocols
Cost Efficiency	Via commercial standards and components, industry capabilities, and reduced physical infrastructure compared with buried cable

A specific WiMAX Forum profile of the IEEE 802.16 standard is proposed for AeroMACS. This enables the aviation community to leverage extensive international standards collaboration and commercially provided components and services (WiMAX Forum, 2011a). Section 5.0 provides more details regarding the WiMAX profile selected for AeroMACS.

3.0   Potential AeroMACS Configuration and Applications

An AeroMACS based on the WiMAX standard for local area networks can potentially support a wide variety of voice, video, and data communications and information exchanges among mobile users at the airport. The airport CNS infrastructure that supports ATM and ATC on the airport surface can also benefit from secure wireless communications by improving availability and diversity.

A wideband communications network can enable sharing of graphical data and near real-time video to significantly increase situational awareness, improve surface traffic movement to reduce congestion and delays, and help prevent runway incursions. AeroMACS can provide temporary communications capabilities during construction or outages, and can reduce the cost of connectivity in comparison to underground cabling. A broadband wireless communications system like AeroMACS can enhance collaborative decision making, ease updating of large databases and loading of flight plans into flight management system (FMS) avionics, and enable aircraft access to system wide information management (SWIM) services for delivery of time-critical advisory information to the cockpit.

3.1   Proposed AeroMACS Network Configuration

To provide services to a potentially large number of mobile users and fixed assets, a standard WiMAX network architecture is proposed for AeroMACS. One or more base stations are required to provide required coverage, availability, and security. Figure 4 illustrates a notional AeroMACS network deployed at an airport. In this notional network configuration, air traffic control and management services can be physically isolated from airlines and airport/port authority services if required. However, WiMAX networks have the capability to integrate multiple services while preserving the desired security and quality of service provisions of each.
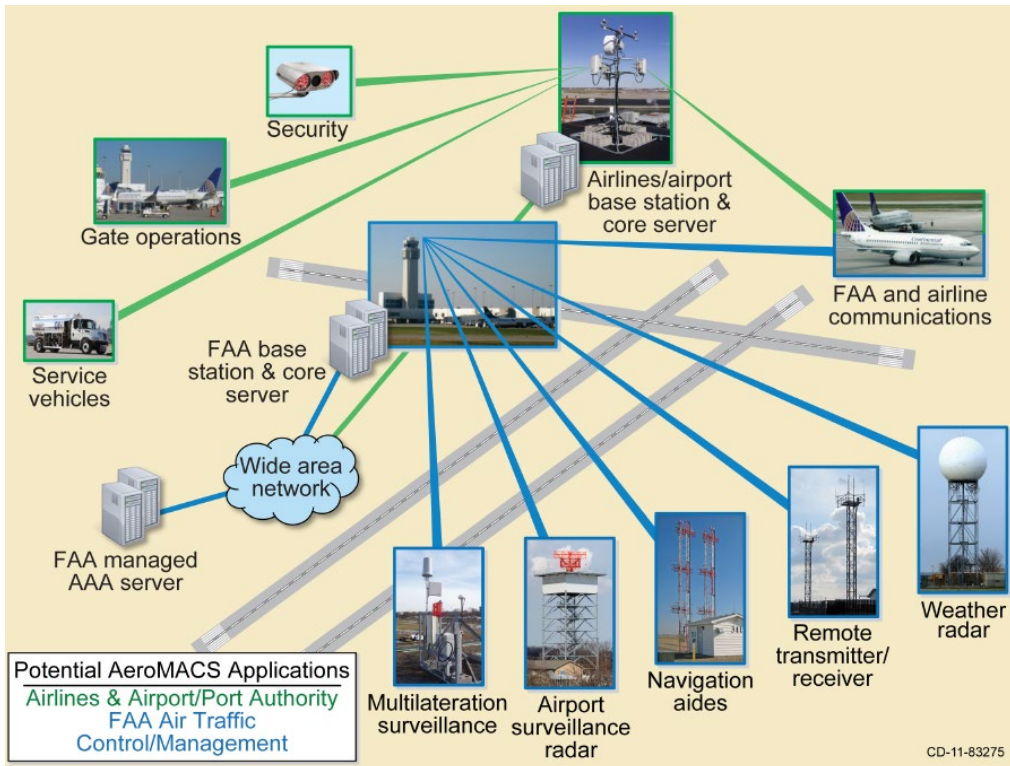
Figure 4.—Notional AeroMACS network configuration and potential applications.

3.2 Categories of Potential AeroMACS Services

The potential services and applications provided by AeroMACS can be grouped into three major categories: ATC/ATM and infrastructure, airline operations, and airport and/or port authority operations (Budinger et al., 2010). Within these broad categories, the data communications services and applications can be described as either fixed or mobile, based on the mobility of the end user. However, because of operational constraints on the international frequency spectrum allocated for AeroMACS (described in Sec. 4.0), only those services that can directly impact the safety and regularity of flight are candidates for provision by AeroMACS. Some examples of potential AeroMACS services and applications are listed in Table 2.

TABLE 2.—EXAMPLES OF POTENTIAL AeroMACS SERVICES AND APPLICATIONS

FAA Air Traffic Control and Infrastructure Applications Examples	
Selected air traffic control (ATC) and air traffic management (ATM)	Mobile
• Surface communications, navigation, surveillance (CNS), weather sensors	Fixed
Passenger and Cargo Airline Applications Examples	
• Aeronautical operational control (AOC)	Mobile
• Advisory information	
– Aeronautical information services (AIS)	Mobile
– Meteorological (MET) data services	
– System wide information management (SWIM)	
• Airline administrative communications (AAC)	Mobile
Airport Operator/Port Authority Applications Examples	
• Security video	Fixed
• Routine and emergency operations	Mobile
• Aircraft de-icing and snow removal	Mobile

3.2.1   Potential Air Traffic Applications

Many candidate mobile ATC/ATM applications are under consideration for future provision via AeroMACS (Apaza, 2010). These include selected messages that are currently conveyed over the aircraft communications addressing and reporting system (ACARS) (e.g., pre-departure clearance (PDC)), selected controller pilot data link communications (CPDLC) messages (e.g., four-dimensional trajectory negotiations (4D-TRAD)), selected COCR services (e.g., surface information guidance (D-SIG)), and other safety-critical applications (e.g., activate runway lighting systems from the cockpit (D-LIGHTING)). Potential fixed infrastructure applications in the U.S. include communications (e.g., controller-to-pilot voice via remote transmit receiver (RTR)), navigation aids (e.g., instrument landing system data for glide slope and visibility data for runway visual range), and surveillance (e.g., airport surface movement detection and airport surveillance radar (ASR)). AeroMACS can also be used to convey electronic equipment performance data for remote maintenance and monitoring (RMM). Most of these existing applications are fixed point-to-point and use voice grade circuits. AeroMACS offers a flexible alternative to guided media (e.g., copper and fiber optic cable). However, the FAA may require separation of these services from the airline and airport services, which are described in the next two subsections.

3.2.2   Potential Airline and Advisory Applications

Mobile AIS/MET services have the potential to become significant drivers of AeroMACS design because of several high-volume data base synchronization services that would benefit from AeroMACS implementation (Apaza, 2010). These include the AIS baseline synchronization service (e.g., uploading flight plans to the FMS and updating terrain and global positioning satellite (GPS) navigational databases and aerodrome charts to electronic flight bag (EFB)), data delivery to the cockpit (e.g., data link aeronautical update services (D-AUS), and airport/runway configuration information (D-OTIS)), and convective weather information (e.g., graphical forecast meteorological information and graphical turbulence guidance (GTG) data and maps).

Passenger and cargo airlines provide another significant source of data and voice applications for potential integration over AeroMACS. These include ground operations and services (e.g., coordination of refueling and deicing operations), sharing of maintenance information (e.g., offload of flight operational quality assurance (FOQA) data), and aircraft and company operations (e.g., updates to flight operations manuals and weight and balance information required for takeoff).

3.2.3   Potential Airport Operator Applications

The airport or port authority operations provide the final category of potential applications for AeroMACS (Apaza, 2010). These are dominated by video applications required for safety services (e.g., fixed surveillance cameras and in-vehicle and portable mobile cameras for live video feeds and voice communications with central control during snow removal, de-icing, security, fire and rescue operations). Finally, AeroMACS can also help ensure compliance with regulations for safety self-inspection (e.g., reporting status of airport runway and taxiway lights and monitoring and maintenance of navigational aids and time critical airfield signage). The full range of candidate applications and services for AeroMACS is under investigation in both the U.S. and Europe (Wargo and Apaza, 2011).

Many of these services and applications are currently provided to mobile users through a mix of VHF voice and data links, land mobile radio services, and commercial local area wireless networks. The fixed communications services and applications at airports are typically implemented via buried copper and fiber optic cables. AeroMACS offers the potential for integration of multiple services into a common broadband wireless network that also securely isolates the applications from each other.

The first safety-critical application expected to migrate to AeroMACS in the U.S. is airport surface detection equipment model X (ASDE-X). For ASDE-X, AeroMACS provides wireless interconnection of multilateration (MLAT) sensors distributed across the airport surface. MLAT data is combined with

surface movement radar data and aircraft transponder information to display detailed information about aircraft position (Sensis, 2011).

The deployment of AeroMACS infrastructure at an airport to enable the migration or augmentation of one of more existing services opens the potential for many additional services, especially those that require wider bandwidth, such as graphical information delivery and video services.

4.0   Spectrum Considerations

This section describes the process leading to an international frequency spectrum allocation for AeroMACS, and modeling to ensure compatibility with other co-allocations in the band.

4.1   Channel Modeling

The provision of a new international frequency spectrum allocation for the future airport surface wireless data communications system was supported by C-band channel modeling and service bandwidth estimation studies. Signal propagation research and channel sounding measurements at 5091- to 5150-MHz were performed by Ohio University and NASA Glenn at airports in the U.S. (Matolak, 2007). Measurements were taken at representative large, medium and small (general aviation) airports.

Thousands of power delay profiles (PDPs) were taken at each airport, along with received signal strength (RSS). In general, wireless communications networks at large airports will experience the most areas of multipath fading and non-line-of-sight (NLOS) conditions. Figure 5 illustrates an example of the time evolution of an NLOS PDP, taken from measurements at JFK Airport.

The example shows how the received components fade in time. Fades of more than 10 dB are evident. The PDP and receive signal strength indication (RSSI) measurements enabled characterization of propagation path loss, fading channel amplitude statistics, multipath persistence and channel statistical non-stationarities, and fading rate. Observations during measurements also revealed highly non-isotropic scattering. The study concluded that the airport surface channel is very dispersive for bandwidths above about 1 MHz and that fading is very dynamic and in some cases severe.

These characteristics were used to develop statistically nonstationary tapped delay line channel models for both high fidelity (HF) and sufficient fidelity (SF). Because of the complexity of the HF models, the study recommended that the SF models be used to evaluate the performance of the proposed IEEE 802.16 systems in the airport surface environment.
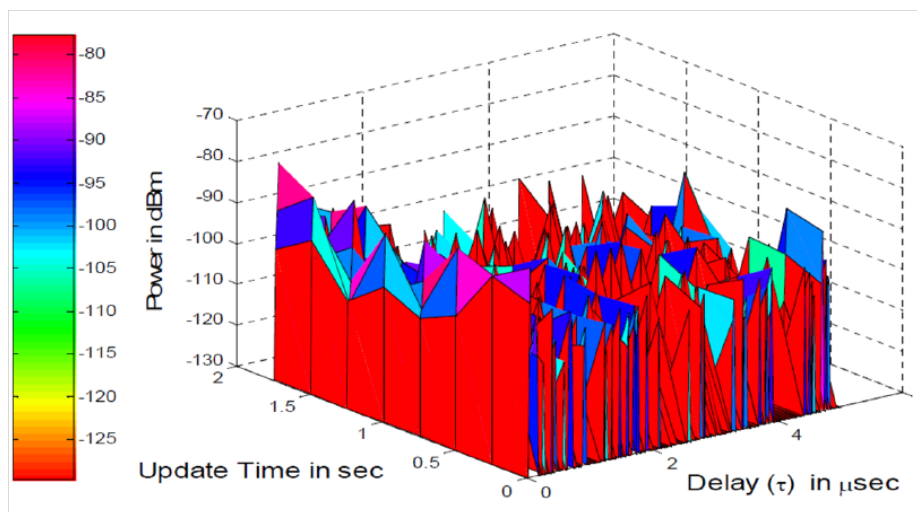

Figure 5.—An example of a power delay profile versus time.

4.2 Bandwidth Estimation for Proposed Spectrum Allocation

Studies to estimate the bandwidth required to provide the potential AeroMACS applications such as those identified in Section 3.0 were conducted in collaboration with the FAA by both NASA and the MITRE Corporation Center for Advanced Aviation System Development (CAASD). An early NASA/FAA study estimated the FAA's existing and anticipated data requirements for instrument landing systems, radar systems, runway visual range, visual aids, and A/G communications (Apaza, 2004). The highest requirements for wireless communications from airlines and port authorities included communications with ground maintenance crews and airport security.

A later study conducted by NASA Glenn estimated additional bandwidth requirements to accommodate wake vortex sensing (to potentially enable closer spacing between arriving aircraft), and the overhead associated with security provisioning features of the IEEE 802.16 standard (Kerczewski, 2006). In a series of studies conducted for the FAA from 2004 to 2008, MITRE CAASD established and refined estimates of the aggregate data rate requirements for a high-data-rate surface wireless network called airport network and location equipment (ANLE) (Gheorghisor, 2008). In alignment with the COCR, these studies addressed potential requirements through 2020 (Phase 1) and beyond 2020 (Phase 2). The bandwidth requirements for proposed mobile and fixed applications using an IEEE-802.16-based system were estimated for both low-density and high-density airports.

The highest total aggregate data capacity requirements for fixed and mobile applications is based on large airports (e.g., Dallas Ft. Worth (DFW)) with a terminal radar approach control (TRACON) ATC facility not collocated with an ATC tower (ATCT). ANLE was envisioned primarily to provide mobile communications with aircraft, but also to support classes of sensors and other fixed and mobile applications within the same network.

4.2.1 Aggregate Data Rate for Mobile Applications

Aggregate data requirements for ANLE were estimated for the following categories of mobile applications for the Phase 2 timeframe, listed in decreasing magnitude:

- Large file transfers from AOC to onboard electronic flight bags (EFBs) such as database updates and graphical weather
- Monitoring and controlling the physical security of aircraft including the provision of real-time video transmission from the cockpit
- Integration and dissemination of situational awareness information to moving aircraft and other vehicles
- Voice over Internet protocol (VoIP) among airline and airport personnel
- Radio frequency identification (RFID) for luggage and other assets.

The estimated aggregate data rate requirement for these mobile applications is nearly 20 Mbps. AOC data accounts for more than half of that.

4.2.2 Aggregate Data Rate for Fixed Applications

Estimates for the following categories of fixed applications for the Phase 2 timeframe, listed in decreasing magnitude are

- Communications from sensors for video surveillance and navigational aids to the TRACON
- TRACON-to-ATCT video, voice, and data communications
- Diversity path for ATC voice to the RTR
- Distribution of weather data products
- Surveillance data from surface radars and ASDE-X sensors.

The estimated aggregate data rate requirement for these fixed applications is over 52 Mbps. The combination of video surveillance and sensors and TRACON-to-ATCT data communications account for about 80 percent of the total.

The combined mobile and fixed data requirements provided the basis for estimating the total amount of radio spectrum needed for the operation of ANLE, now referred to AeroMACS. Based on analysis of an IEEE 802.16 system, two different base station channel bandwidth configurations (multiple 10-MHz and 20-MHz channels) and modulation techniques, an upper bound of 60 MHz of new spectrum was estimated in order to support the envisioned applications in the 2020 timeframe and beyond. The ITU-R expects that 60 to 100 MHz of spectrum will be required for the future surface domain (ITU-R, 2007).

4.3 International Spectrum Allocation

At the International Telecommunications Union World Radiocommunication Conference held in late 2007 (WRC-07), Agenda Item 1.6 invited participants "to consider allocations for the aeronautical mobile route service (AM(R)S) in parts of the bands between 108 MHz to 6 GHz, and to study current frequency allocations that will support the modernization of civil aviation telecommunication systems." At the conclusion of WRC-07, a new AM(R)S co-primary allocation in the 5091 to 5150 MHz band was added to the International Table of Frequency Allocations. The new allocation is limited to surface applications at airports. This allocation is in a region of the frequency spectrum commonly referred to as C-band.

This specific 59 MHz of spectrum is also referred to as the microwave landing system (MLS) extension band. MLS carries an aeronautical radio navigation services (ARNS) allocation. The WRC-07 decision on Agenda Item 1.6 essentially removed the prior limitation for support of ARNS only. Along with the existing MLS and new AeroMACS services, the other co-primary service allocations in this band include Earth-to-Space satellite feeder links for non-geostationary orbiting (GSO) mobile satellite service (MSS), and new co-allocations for aeronautical mobile telemetry (AMT) used with research aircraft during test flights and an aeronautical mobile service (AMS) limited to aeronautical security (AS).

The AM(R)S communications are defined as safety communications requiring high integrity and rapid response. Generally these include ATC and those AOC communications that support safety and regularity of flight (Biggs, 2008). In the U.S., AeroMACS networks are expected to be approved for both mobile and fixed applications that directly support safety and regularity of flight. AeroMACS services can be provided to aircraft anywhere on the airport surface, as long as wheels are in contact with the surface. AeroMACS can also be used for communications with a variety of service vehicles and airport infrastructure that directly support safety and regularity of flight.

The protected allocation for AM(R)S in this portion of C-band enables ICAO to approve international standards for AeroMACS wireless mobile communications networks on the airport surface. Based on expectation of high demand for AeroMACS services, Agenda Item 1.4 for WRC-12 will consider additional allocation of AM(R)S spectrum within the 5000 to 5030 MHz band.

4.4 Modeling for Interference Compliance

The co-allocation for AeroMACS at WRC-07 includes provisions to limit interference with other co-primary terrestrial services—MLS, AMT, and MSS feeder links. In the U.S., essentially no airports use the MLS for precision landing assistance. That need has been largely met through the wide area augmentation system (WAAS) that is based on GPS data. A limited number of airports in Europe use MLS. At those airports, coordination for equitable sharing of the 59-MHz allocation will be required to prevent mutual interference. In similar fashion, civilian airports near the specific locations where AMT is used on test aircraft will need to coordinate on the use of specific AeroMACS channels and AMT transmissions in order to limit potential interference. However, potential interference from hundreds of AeroMACS-equipped airports across the continents into MSS feeder link receivers on orbiting satellites is global in nature. In specific, the potential for co-channel interference from AeroMACS into the Globalstar

MSS feeder link receivers must be mitigated though practical limits, international standards, and compliant implementations across the nations' airports.

NASA Glenn is modeling the interference caused by AeroMACS in order to help establish practical limits on the total instantaneous power that could eventually be radiated from hundreds of airports across the NAS (Wilson and Kerczewski, 2011). In order to ensure that the MSS feeder link threshold is not exceeded, the total radiated power recommended for each potential AeroMACS-equipped airport must take into consideration the total radiated power from all potential AeroMACS-equipped airports across the NAS. NASA Glenn uses Visualyse Professional Version 7 software from Transfinite Systems Limited to model the potential interference.

Figure 6 illustrates the aggregate interference power at a single Globalstar satellite receiver orbiting at 1414-km from AeroMACS emissions at a total of 757 towered airports across the U.S. and the Caribbean, including 34 in Canada, and 20 in Mexico. For this condition, the model assumes each airport radiates 5.8-W omni-directionally in the 20-MHz channel that spans the Global receiver's 1.23 MHz bandwidth.

Based on an interpretation of the final resolutions of WRC-07, the AM(R)S co-allocated services must not increase the thermal noise temperature of Globalstar feeder link receivers by more than 2 percent (Gheorghisor et al., 2009). This corresponds to a threshold of –157.3 dBW for total interference power from AeroMACS into Globalstar feeder link receivers. In order to prevent the interference power from exceeding this threshold at any point in the Globalstar receiver orbit, the model shows that the omni-directional transmitters at each of the 757 airports needs to be limited to 799-, 401-, and 201-mW for 20-, 10-, and 5-MHz channels, respectively (Wilson and Kerczewski, 2011).

Further enhancements to the realism of the airport infrastructure modeling and correlation with experimental performance measurement data from the AeroMACS prototype are underway at NASA Glenn. Enhanced models will be used to develop a final set of recommendations on AeroMACS radiated power limits based on 5-MHz channels (Gheorghisor et al. 2011).
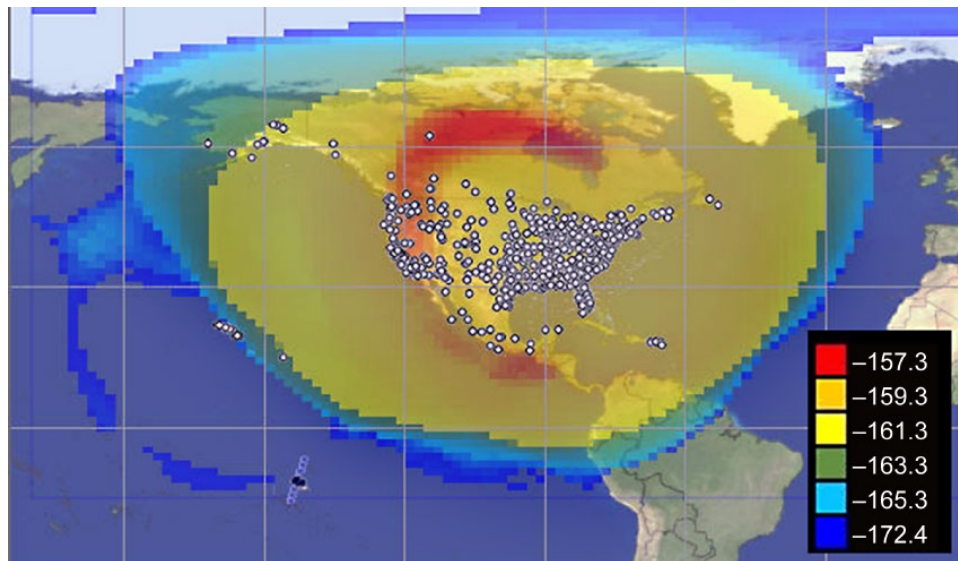

Figure 6.—Modeled interference power distribution from 757 AeroMACS-equipped airports in North America as seen at a Globalstar receiver orbiting 1414 m above the Earth's surface.
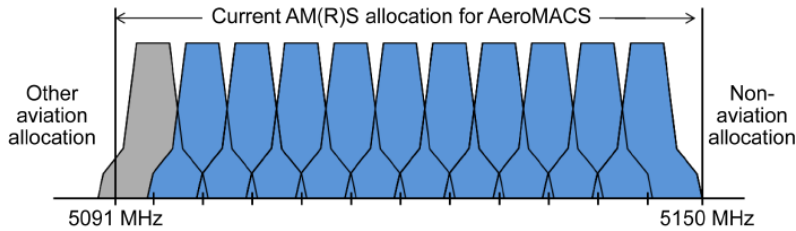
Figure 7.—Proposed AeroMACS channel plan for 5091 to 5150 MHz allocation.

4.5 Proposed AeroMACS Channelization

The location of AeroMACS channels within the 5091- to 5150-MHz allocation takes into consideration a number of factors. Among those are efficient utilization of current and potential future spectrum allocations; guard bands to limit out-of-band radiated power; anticipated number of AeroMACS BSs and SSs; practical limits on frequency spectrum reuse; the bandwidth requirements of potential AeroMACS applications described previously; and compliance with WiMAX Forum standards.

The channel plan illustrated in Figure 7 shows the recommended AeroMACS channel plan. It includes 5-MHz channels on equally spaced center frequencies from 5095- to 5145-MHz. Assuming coordination with other aviation allocations in the band directly below 5091 MHz (to limit the effects of interference) enables up to 11 separate AeroMACS channels. This plan can be extended to accommodate additional 5-MHz channels for a future allocation within the 5000 to 5030 MHz spectrum (Budinger et al., 2010).

5.0 International Standards Process

This section summarizes the process, findings, and recommendations provided by the FAA, NASA Glenn and ITT to advance the application of a specific IEEE 802.16 profile as the basis for the AeroMACS standard. A standard profile for AeroMACS ensures that all stakeholders—test equipment vendors, integrated circuit vendors, as well as the aviation industry—are capable of supporting AeroMACS development, and that global deployments will be interoperable. The profile is used as a guide for development of minimum operational performance standards (MOPS) for AeroMACS avionics. In the U.S., an RTCA Special Committee on Airport Surface Wireless Communications, SC-223, was established in July 2009 to develop the AeroMACS profile and MOPS (RTCA SC-223, 2011). The U.S. final draft profile was completed at the end of 2010 and the MOPS document is scheduled to complete by the end of 2011. The AeroMACS profile and MOPS are developed in close coordination with EUROCAE Working Group WG-82 in Europe. Common AeroMACS standards in the U.S. and Europe are requested by ICAO in part to be responsive to the recommendation of ANC-11 for global interoperability and to help expedite ICAO approval of international AeroMACS standards.

The AeroMACS profile closely follows the format and substance of profiles developed by the WiMAX Forum for commercial and industrial use. The WiMAX Forum is an industry consortium whose primary technical function is to develop the technical specifications underlying WiMAX Forum Certified products. An ad-hoc joint committee was established between RTCA SC-223 and the WiMAX Forum in August 2010, to facilitate development of an AeroMACS profile. The profile is expected to be incorporated as one of several WiMAX Forum Certified profiles.

5.1 WiMAX Forum Profiles

The initial RTCA AeroMACS profile is based on the WiMAX Forum Mobile System Profile Specification Release 1.0 because it is currently the only release recommended by the WiMAX Forum for hardware certification use. Release 1.5 has been approved by WiMAX Forum but is not implemented for hardware certification because the IEEE 802.16m amendment is expected to be implemented soon via

profile Release 2.0. The RTCA SC-223 and EUROCAE WG-82 decided jointly not to implement features of the upcoming profile Release 2.0 at this time. Thus, the AeroMACS standard is currently based on Release 1.0.

Release 1.0 is published in three main parts: (1) COMMON Part, (2) Time Division Duplex (TDD) Part, and (3) Frequency Division Duplex (FDD). However, AeroMACS is recommended to be a TDD-only system, so only the first two parts of the WiMAX Forum profile are applied to AeroMACS (WiMAX Forum, 2011a).

5.2   Joint RTCA – EUROCAE Process

The AeroMACS profile has been developed through a series of RTCA and EUROCAE meetings and telephone conferences, often with WiMAX Forum participation. SC-223 and WG-82 leadership participate in most plenary meetings of each other's organizations.

A joint RTCA and EUROCAE meeting was held in Brussels, Belgium, in late September 2010 with participation by members of the WiMAX Forum via telephone conference in which many profile parameter settings were established for AeroMACS. A fully harmonized profile was established during the RTCA SC-223 Plenary Meeting No. 8 in November 2010. This harmonized profile is available on the RTCA SC-223 website; however, permission from RTCA is required to access the workspace where these documents are posted. The profile description at this site includes a rationale statement for each chosen setting.

The joint AeroMACS profile completed in December 2010 is considered as the RTCA "final draft" version. EUROCAE plans to continue their studies throughout 2011, leading to a "final joint profile" by the end of 2011. The final joint profile may differ from the 2010 final draft profile based on results of the EUROCAE studies. EUROCAE plans to complete validation tests before publishing a final AeroMACS profile by the end of 2013.

Commercial WiMAX networks have been successfully deployed in 140 countries as of May 2009. This global acceptance of the WiMAX standard, and U.S. interoperability with the AeroMACS standard approved by EUROCAE in Europe, is expected to ease acceptance and ICAO approval of the global AeroMACS standard for aeronautical mobile applications on the airport surface.

6.0   AeroMACS Prototype Network

This final section of the paper discusses the development and evaluation of an AeroMACS prototype network. The FAA-sponsored AeroMACS research is identified in the FAA's NextGen Implementation Plan for 2009 and 2010. A reimbursable Space Act Agreement between NASA Glenn and the FAA enables collaboration between these two agencies and contracted support from ITT for AeroMACS research, development, and service demonstrations.

The world's first AeroMACS prototype was completed in late 2009 for validation of airport surface concepts and verification of communications performance requirements. The AeroMACS prototype is deployed within the Communications, Navigation, and Surveillance (CNS) Test Bed located at NASA Glenn and adjacent Cleveland Hopkins International Airport (CLE). In the following subsections, a description is provided of the AeroMACS prototype and some of the practical technical tradeoffs associated with coverage, cost, and performance, followed by initial results of AeroMACS performance experiments.

Full details of the multiple-year AeroMACS research, development, and experimental effort are available in a two-volume final report (Hall et al., 2011, Hall and Magner, 2011). The first volume addresses concepts of use, initial system requirements, architecture, and AeroMACS design considerations. The second volume describes AeroMACS prototype performance evaluation and provides final recommendations.
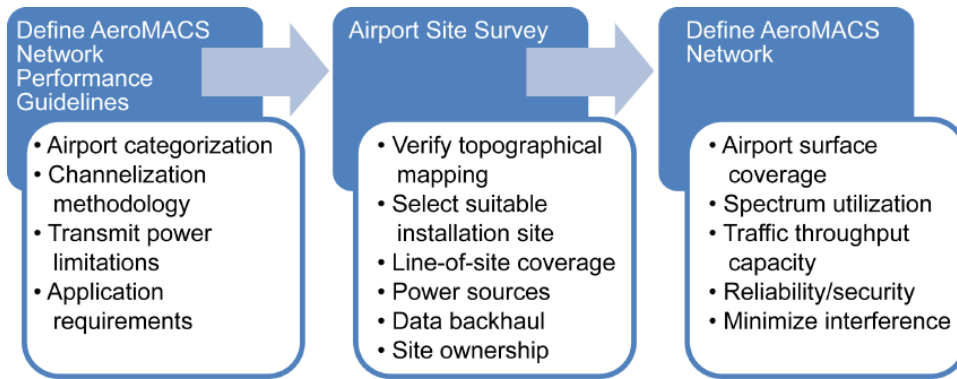
Figure 8.—AeroMACS network design process.

6.1 AeroMACS Prototype Design Considerations

The AeroMACS prototype within the NASA-CLE CNS Test Bed is designed to implement the proposed AeroMACS features that are required to provide modern secure broadband wireless data communications at operational airports across the NAS. An essential element in the design and deployment of an AeroMACS network is a comprehensive radio frequency (RF) or physical layer (PHY) design.

An accurate RF design ensures that the deployed wireless network provides the necessary coverage, capacity, and reliability, with minimal interference, that satisfies the service requirements. Although it is possible to gauge the performance of radio links through theoretical means, real-life deployments must take into account variables from the environment to achieve optimal performance and minimize coverage holes and RF co-channel interference.

Figure 8 illustrates a top-level process for designing AeroMACS networks. The network design process begins with a physical site survey to gather information about the deployment location. A site survey provides an opportunity to validate any topography mapping information that may be available. It is also used to identify suitable installation locations for AeroMACS equipment. A site survey also provides input to the next three phases of the RF design process—coverage model, spectrum analysis, and capacity analysis.

6.1.1 Coverage Model

The coverage model requires a map of the site along with coordinates of potential locations for base stations (BSs) and user terminal subscriber stations (SSs). The coverage model must account for the impact of the environment on RF transmissions, including the effects of the topography, physical obstructions, and foliage. These effects introduce propagation loss and delays that have been cataloged in reference models. In addition, clutter models or obstruction densities are also modeled in this phase. Clutter models represent the density of obstructions in the deployment site. Typical options include rural, urban, and suburban clutter models. An airport surface with its relatively open runways and taxi areas and congested terminal areas will require a combination of the three models.

In addition to considerations of site topology and propagation delays, general parameters of the AeroMACS solution must be identified. Notable parameters include BS and SS transmit/receive power, antenna gains, feeder losses, BS and SS heights, and orthogonal-frequency-division multiple access (OFDMA) radio-access-related parameters. In addition, the following are the relevant system design parameters:

- Fade margin allocation for required link reliability
- Antenna gain and polarization diversity
- Co-channel interference margin

- Modulation and error correction
- Uplink to downlink transmit ratio (UL/DL ratio) for TDD mode
- Data throughput capacity requirements, including excess capacity margin
- BS and SS receiver noise figures
- Maximum BS and SS output/input power

Finally, a link budget must be calculated that specifies the maximum path loss between BS and SS locations. Receiver sensitivity for supported modulation schemes can be obtained from the BS and SS vendor data sheets. Characteristics of the BS and SS and information about the placement and types of antennas are used to generate an accurate coverage map.

6.1.2   Spectrum Analysis

The spectrum analysis phase of the network design involves analysis of a potential site for interference. This includes both interference into the proposed AeroMACS and the potential for AeroMACS to interfere with co-allocated services. Interferers can include emissions at the fundamental frequency plus transmitter harmonics and inter-modulation emissions.

Proper analysis involves measurement of the maximum transmitter signal levels to determine how much energy is present across the surveyed RF band of interest. In the case of AeroMACS, C-band is the band of interest. The spectrum analysis can be conducted at ground level, but it is typically conducted from elevated locations including rooftops and tower sites at least 16 m high.

6.1.3   Capacity Analysis

Capacity analysis involves calculating how much traffic can be supported given the UL/DL ratio and the anticipated traffic patterns with the specified bandwidth and modulation scheme. The parameters used for capacity calculations include:

- TDD UL/DL ratio
- Modes of operation
- Channel bandwidth
- Subcarrier allocation scheme
- Transmit to receive guard ratio timing

The theoretical PHY throughput per modulation scheme can be calculated using the following formula (Upase et al., 2007):

$$R_b = R_s \, MC/R_r \tag{1}$$

Where:
  M modulation gain (2 for quadrature phase-shift keying (QPSK), 4 for 16-quadrature amplitude modulation (QAM), and 6 for 64-QAM)
  C coding rate (1/2, 3/4, 2/3, or 5/6)
  R_r repetition rate (1, 2, 4, or 6)
  R_b bit rate
  R_s symbol rate

Equation (1) accounts for the AeroMACS modulation OFDMA pilot overhead but does not account for the signaling overhead. The signaling overhead depends on the number of active connections and the service types used. Studies have found that signaling overhead may vary from 4 to 10 percent of physical layer (PHY) throughput. Estimates of capacity using RF design tools take into consideration the impact of multiple-input, multiple-output (MIMO) antenna schemas to enhance coverage and/or capacity.

Although theoretical and software-based tools provide a baseline for determining the capacity of an AeroMACS network, it will be necessary to make minor adjustments once the network has been implemented. Such optimization involves selecting appropriate network parameters that will support the Quality of Service (QoS) requirements. A thorough mobile test drive throughout the deployed network is the final step for collecting network performance data for analysis and optimization.

6.2   AeroMACS Prototype Network Architecture

The AeroMACS prototype was architected according to the reference network model developed by the WiMAX Forum Network Working Group (WiMAX Forum, 2011b). The reference network model is designed to enable interoperability of vendor equipment and to provide a structure for the deployment of new systems. The architecture is Internet Protocol (IP) based, meaning it relies on IP addressing to provide secure connectivity between users and access to common services. All WiMAX reference model elements are used to implement the AeroMACS prototype network. These include: mobile SSs, stationary BSs, the access services network (ASN) function, and the connectivity services network (CSN) functions. The CSN functions include authentication, authorization, and accounting (AAA) and network management system (NMS).

6.3   AeroMACS Prototype Implementation

The AeroMACS prototype uses commercial WiMAX from the BreezeMAX (Alvarion, Ltd.) product line. Two BSs are included in the AeroMACS prototype to provide coverage redundancy and at least two opportunities for a mobile SS unit to link with a BS. One BS is located on NASA Glenn property and the second BS is on the CLE airport. Multiple base transceiver station (BTS) sectors are implemented at each BS to increase coverage, link sensitivity, and data capacity. The network includes ASN–gateway CSN functions to provide QoS control, user authentication and authorization for security, and mobility handoff between BSs and adjacent BTS sectors.

Many of the decisions about network layout for implementing the AeroMACS prototype in the NASA-CLE CNS Test Bed were driven by the need to use existing mounting structures for the BS and fixed SS sites, the desire to integrate with pre-existing test bed MLAT sensor sites, and the fact that the AeroMACS prototype is intended for experimental and demonstration purposes. As such, it does not interact with live airport operations and is not optimally configured for use as an operational system.

Figure 9 shows the placement of the two AeroMACS prototype BS sites in the NASA–CLE CNS Test Bed. BS-1, mounted on the tower adjacent to NASA Glenn's Flight Research Building (B4) hangar office, has two BTS sectors that are directed at 55° and 200° azimuth from true north. These are mounted 20 m above ground level as shown in the upper-left inset photograph in Figure 9. BS-2, located on the roof of the Aircraft Rescue and Firefighting (ARFF) building located on CLE airport property, has three BTS coverage sectors directed 45°, 185°, and 295° from true north. The antenna mast and AeroMACS outdoor units (ODUs) are shown in the lower-right inset photograph in Figure 9. The ODUs are mounted to the mast on standoff arms to increase separation and RF isolation between units to thereby decrease the potential for in-band interference.

GPS outdoor units are mounted above each BTS ODU. Two are mounted on the tower at BS-1 at 3 m above each BTS ODU, and three are mounted at BS-2, one for each BTS ODU. The GPS ODUs support precise timing and transmit/receive synchronization between BTS sectors. An option to reduce cost is to locate one GPS ODU per BS site and "chain" the GPS timing signal between ODUs. The coverage area of each BTS sector is 90° in azimuth as determined by the –3-dB pattern roll-off of the BTS sector antenna. These sector-coverage placements provide a high-degree of redundant coverage across the desired coverage area, including the runways, most of the taxiways, and much of the ramp areas.
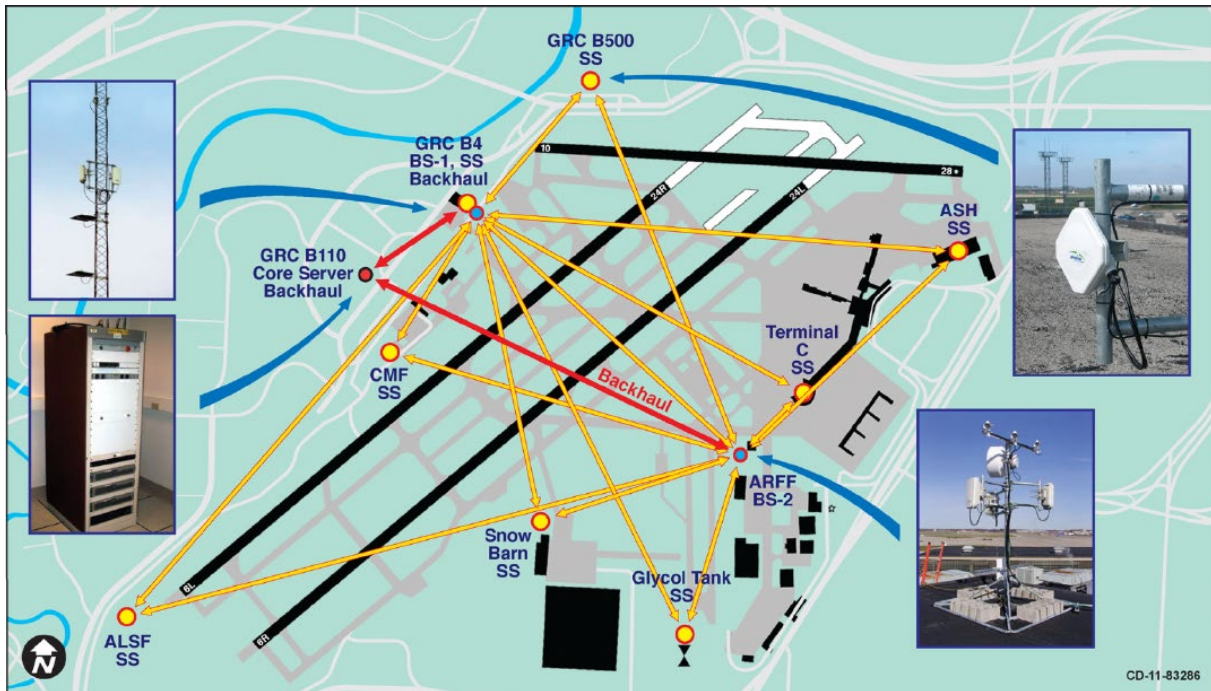
Figure 9.—NASA–CLE CNS Test Bed showing locations of the AeroMACS prototype base stations, fixed subscriber stations, microwave backhauls, and core server.

Data from each BS site is transported to the core server using wireless backhaul links that operate in a licensed 11-GHz commercial band. A pair of these microwave radios is used on the roof of NASA Glenn's Space Experiments Building (B110) in full duplex operation between each BS site and the core CSN servers located in B110.

Figure 9 also shows the placement of SSs at eight fixed sites. Each of these sites was chosen for its co-location with MLAT surveillance sensors that were previously installed by the Sensis Corporation in NASA-CLE CNS Test Bed through a cooperative agreement with NASA Glenn. The Sensis MLAT sensors in the test bed were previously interconnected in a fixed wireless mesh network configuration that was based on the IEEE 802.11 standard (DeHart and Budinger, 2008). In the AeroMACS prototype, data from each MLAT sensor is transmitted wirelessly over the IEEE 802.16-based network to a central surveillance data processor. These MLAT sites are representative examples of fixed CNS infrastructure that AeroMACS can support within a mobile communications network on the airport surface.

A weatherproof enclosure is mounted near each SS as shown in Figure 10 only to support testing of the AeroMACS network. An operational AeroMACS network does not require such support equipment. The photograph shows the electronics equipment partially wired during construction. Each enclosure includes a single-board computer, a managed Ethernet switch, and power supplies to enable performance testing and applications demonstrations. The single-board computer hosts a Linux operating system and IxChariot (Ixia) software for network performance tests. The IxChariot software generates test data streams that are used to test communication link capabilities. A test console is located at the core server in NASA Glenn B110 to coordinate the execution of tests, collect IxChariot test results through the network, and compute statistics of network performance. Existing airport sensors, such as the MLAT surveillance remote units, can be connected as live data sources in place of, or in addition to, the IxChariot software test data streams. A port on the managed switch is the interface for IP-based sensors such as the Sensis MLAT sensors.

Figure 10.—Electronics equipment supporting prototype fixed
subscriber stations during testing.

6.3.1 Emulation of Surface Vehicle Mobility

The range of vehicles that may use an operational AeroMACS network for communications vary from slow service vehicles (that mostly operate in terminal areas) to aircraft (that enter the network at relatively high-speed shortly after landing). The mobile environment for an arriving aircraft will transition from the mostly open, low-multipath conditions of the movement area to the terminal and gate area where multipath will increase but ground speeds are lower. The propagation environment will transition back to high speeds in mostly open areas as the aircraft departs the terminal gate and taxis for takeoff.

The NASA Aeronautical Research Vehicle (ARV), shown in Figure 11, was modified for use as a mobile AeroMACS SS under the various conditions expected for the airport surface environment.

An AeroMACS SS unit and two antennas were mounted on the roof of the ARV to support mobile AeroMACS tests. An aluminum plate was used to form a ground plane for the two AeroMACS antennas as shown in Figure 11. A mobile AeroMACS SS unit, modified with RF connectors for attachment of external antennas, was mounted beneath the aluminum plate. The onmidirectional antennas used in the mobility tests are model SWA2459/360/20/V_2 from HUBER+SUHNER. These antennas exhibit constant gain of +8 dBi in ground plane directions. The gain pattern peaks toward the horizon because of the antenna orientation on the ARV.

Several fixed performance experiments and a set of initial mobility performance tests have been conducted successfully within the NASA-CLE AeroMACS prototype. Initial tests have explored the unique propagation conditions of an airport surface environment at C-band frequencies and the effects of AeroMACS profile parameter settings. Data throughput and packet integrity are measured for 5-MHz channel bandwidths for both stationary and mobile SSs.

The mobile SS integrated into the ARV was used to measure the performance at representative speeds of vehicles on the surface. The ARV was also used to verify the performance requirements to provide AeroMACS services on runways, taxiways, ramp areas, and gates. Initial mobility testing explored the transmit power required to maintain a minimum level of link performance for mobile SSs at vehicle speeds up to 50 knots using both single antenna and multiple-input multiple-output (MIMO) antenna diversity. Findings and recommendations are described in the following sections.
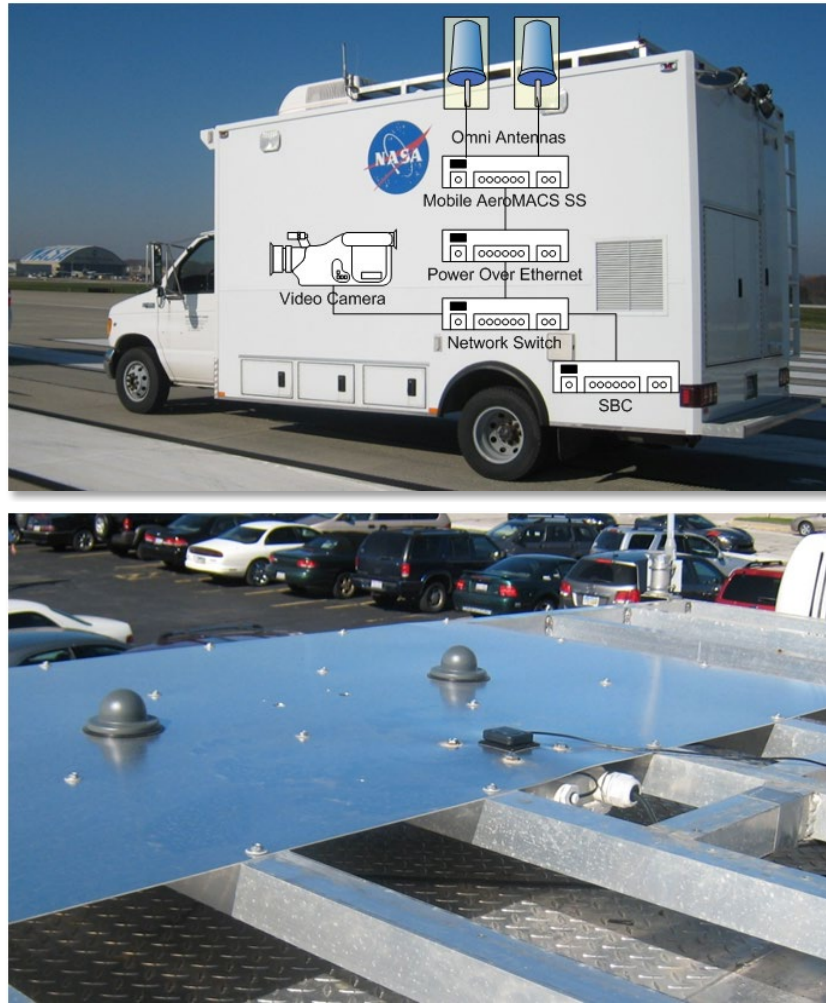
Figure 11.—AeroMACS mobile SS logical network superimposed on NASA Glenn Aeronautical Research Vehicle and roof-mounted omni-directional antennas for mobility testing.

6.3.2 Runway Drive Tests

The first in a 2-month series of mobile AeroMACS drive tests in the U.S. was conducted using the NASA ARV at the CLE airport on runway 24L/6R on 12 October 2010. Runway 24L is approximately 3 km in length, providing an opportunity to test AeroMACS air link ranges up to approximately 1.71 km. In addition to reduced signal strength caused by increased range, signal strengths also vary because of the antenna gain rolloff of the sectorized BS antenna. The positions of BS-1 and BS-2 relative to runway 24L/6R are marked in Figure 12.

The sector antenna pointing directions are indicated by white arrows for the BTS sectors (two for BS-1 and three for BS-2). The BTS sector antennas have a 90° half-power (–3 dB) beam width. The approximate–3 dB boundaries are indicated in Figure 12 with dashed lines for the two sectors used most often in these tests. The ARV travelling along runway 24L in the southwest (SW) direction experienced varying signal levels from a combined effect of changing range and BS sector antenna gain variation as the aspect angle changes.

Drive speed was nominally 40 kt. Tests were conducted with the mobile SS antenna system in MIMO and SISO modes. Network performance was evaluated by generation of bi-directional traffic using network test software. AeroMACS radio and network parameters were set up according to Table 3 for these tests.
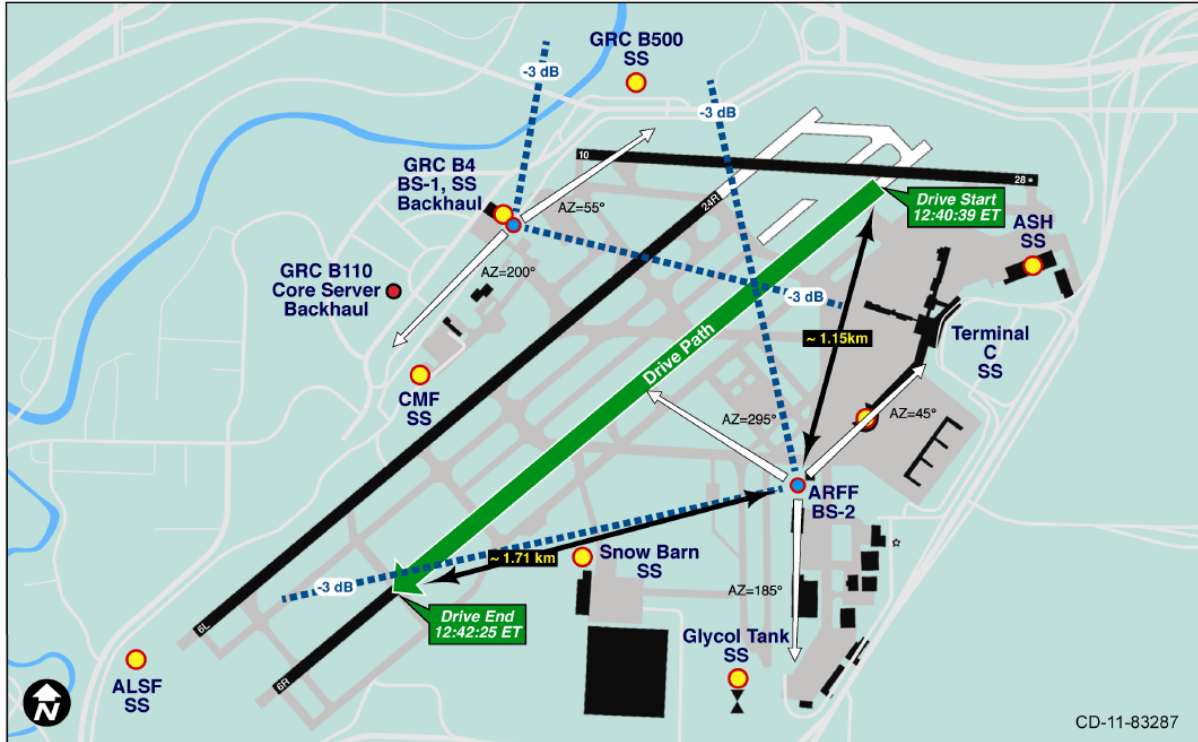
Figure 12.—AeroMACS mobility drive test on Runway 24L.

TABLE 3.—AeroMACS PARAMETER SETTINGS FOR RUNWAY DRIVE TESTS

AeroMACS Parameter	Setting				
AAA server	Enabled				
PKMv2, EAP-TTLS security	Enabled				
AES-128 air link encryption	Enabled				
Maximum transmission unit size	1440 bytes				
DL/UL ratio	60/40				
HARQ	Enabled				
MIMO	Matrix A mode enabled				
Channel bandwidth	5 MHz				
Quality of service (QoS)	Best effort				
BTS number	BTS1-1	BTS1-2	BTS2-1	BTS2-2	BTS2-3
BTS center frequencies, MHz	5100	5140	5130	5120	5110
BTS Tx power, dBm	21	21	21	21	21

A plot of DL (BS to SS traffic direction) throughput during an ARV drive test along runway 24L in the SW direction is shown in Figure 13. The antenna configuration for this test uses two transmit antennas for the BS and 2 receive antennas for the mobile SS that is mounted on the ARV. This DL antenna configuration is referred to as 2 by 2 MIMO Matrix A (Space Time Block Coding). The highest average throughput expected on DL in a 5 MHz channel is 7.5 Mbps, which was achieved mid-way through the drive test. This corresponds to QAM64 modulation, the highest-order modulation supported by the standard.

The IEEE 802.16 standard specifies an adaptive modulation feature for the SS that adapts the modulation rate according to link conditions with the goal of adapting data throughput rate to the highest level supportable by current link conditions. Test traffic throughput was reduced at the start and finish of the drive path, consistent with reduced modulation rate because of added propagation loss and BS sector antenna gain roll-off.
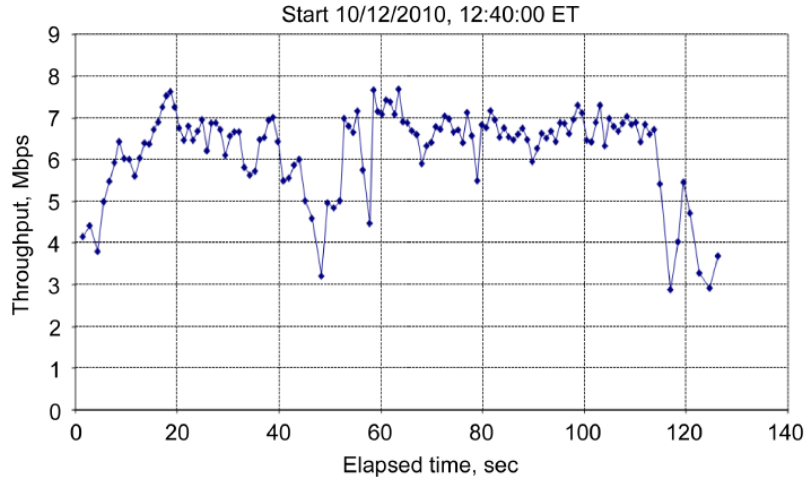
Figure 13.—Downlink throughput in MIMO antenna mode during drive
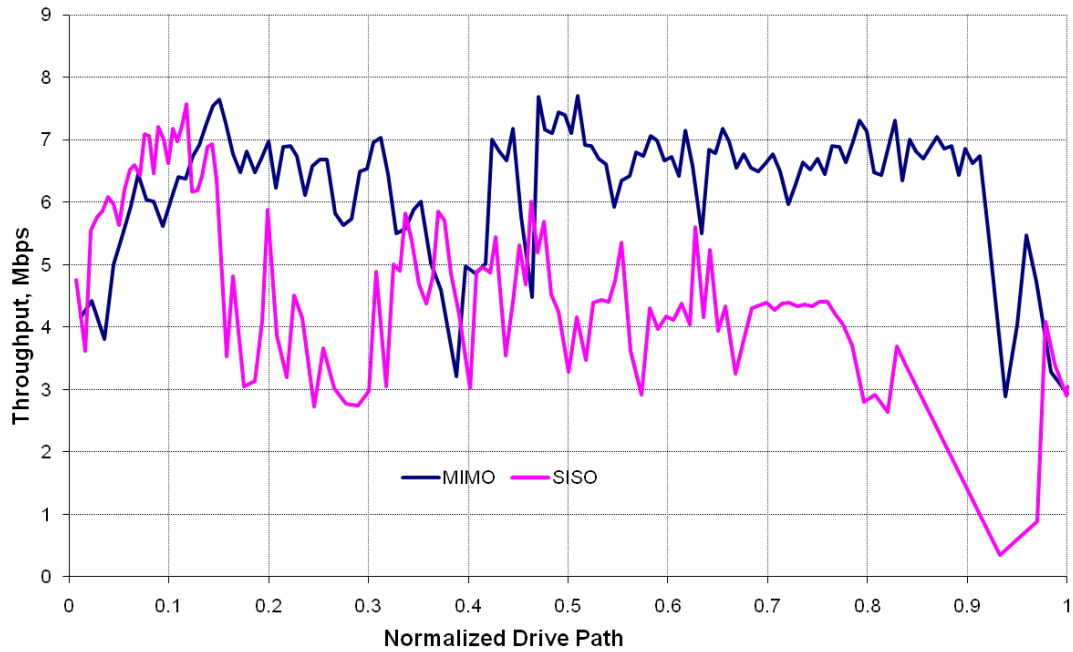test on Runway 24L.

Figure 14.—Comparison of downlink throughput in MIMO and SISO antenna modes.

TABLE 4.—MIMO AND SISO MOBILE ANTENNA
CONFIGURATION THROUGHPUT COMPARISON

Test time	Antenna mode	Throughput average, Mbps	Throughput minimum, Mbps	Throughput maximum, Mbps
1640 GMT	MIMO	5.13	2.70	7.70
1708 GMT	SISO	3.89	0.35	7.57

The plot in Figure 14 compares the throughput performance of MIMO and SISO antenna configurations along the same drive path and for service provided by the same sector of BS-2 in both cases. A comparison of MIMO versus SISO throughput along the drive path shows that the MIMO antenna configuration achieved greater minimum and average throughput rates. Throughput averaged over the drive tests for MIMO and SISO antenna configurations are compared numerically in Table 4.

The runway 24L tests provide an initial assessment of mobile station antenna configuration impact on performance. The MIMO drive tests provide information on a unique antenna combination. The BTS antenna configuration is 2 by 2 MIMO in the AeroMACS prototype. Two antennas are arranged orthogonally to provide dual 45° slant polarization relative to the ground horizon. This test configuration represents a realistic scenario where BTS antennas use 45° slant-polarization to be compact and the SS antennas are spatially separated on a ground plane as they will be for an aircraft installation.

6.3.3 Base Station Transmit Power Requirements

BS transmit power level requirements were evaluated through a series of drive tests with the mobile ARV SS. Transmit power levels must be chosen to provide communication coverage across an airport surface while also minimizing potential interference to co-allocated users of the AM(R)S 5091- to 5150-MHz band. The survey of BS signal strength across the airport surface was used to assess whether adequate signal is radiated by the BSs. The signal strength survey was completed with a BS transmit power of +21 dBm (125 mW) to provide a benchmark level.

Drive tests along runway 24L were further analyzed for their implications for BTS transmit power requirements to provide an initial assessment of transmit power requirements. Additional analysis should be completed with future test data under additional drive test conditions. The ARV drive path driven at 1640 GMT is shown in Figure 12 with link distances shown from BS-2 to the start and end positions for the drive. The end of the drive provides the longest path distance of 1.71 km.

RSSI is a function of the link distance and BTS sector antenna gain. Real-time RSSI values from the ARV SS can be read periodically. These RSSI values are plotted in Figure 15 and are overlaid with data throughput measurements. Correlation between SS RSSI and throughput rate can be observed with higher RSSI readings (less negative) generally yielding higher throughput rate. The Yellowfin (Berkeley Varitronic Systems, Inc.) receiver provides another method of RSSI measurement. The Yellowfin instrument is programmed to scan through the AeroMACS frequency range searching for valid BS transmissions. RSSI is recorded with reference to the BS center frequency when a valid BS transmission is detected. BS transmissions are received through a 0-dBi gain antenna mounted on the roof of the ARV.
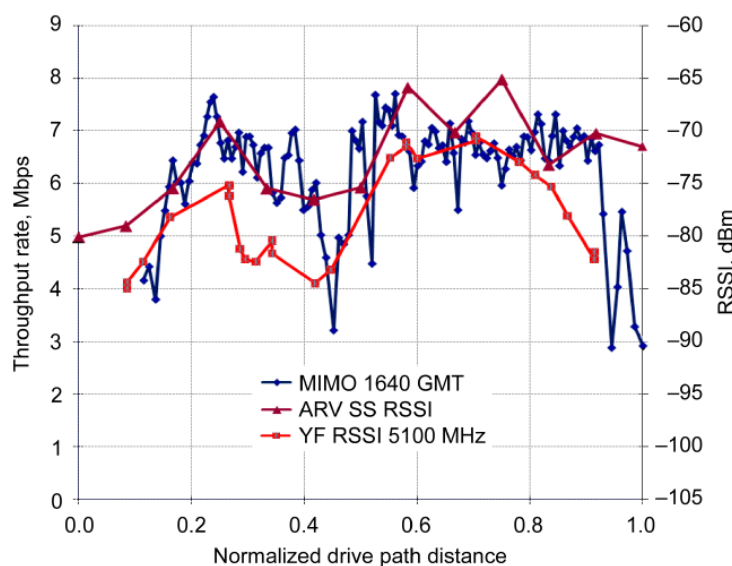

Figure 15.—Runway 24L drive test RSSI and throughput.

The ARV SS maintained service from the same BTS sector throughout the drive test shown in Figure 12. RSSI values recorded by the Yellowfin at the BTS2-3 center frequency of 5100-MHz are also plotted in Figure 15. Again, a correlation can be observed between Yellowfin and ARV SS measured RSSI and throughput rate derived by IxChariot. Lower RSSI readings from the Yellowfin compared to the SS readings can be attributed to its lower receive antenna gain of 0 dBi compared to 8 dBi for the ARV antenna.

A few interesting performance characteristics can be observed in Figure 15 as follows:

1. Throughput rate was reduced as expected at the drive path start and end where lower signal strength occurred because of increased link path loss and decreased BTS sector antenna gain.
2. DL throughput reached a rate of 7.5 Mbps, the highest rate expected for a 5 MHz channel bandwidth, 60/40 percent TDD ratio, and MIMO Matrix A antenna configuration.
3. RSSI readings from the ARV SS and the Yellowfin decreased and hence the throughput rate decreased unexpectedly from 20 to 50 percent of the drive path. The cause of this reduced RSSI is unknown; it might be caused by an unwanted variation the BTS sector antenna pattern.
4. A minimum throughput rate of 3 Mbps was maintained over the length of Runway 24L. This included a maximum link path of 2.2 km at the –3 dB BTS sector pattern.
5. Link connectivity was maintained at vehicle speeds of at least 40 kt.

The operating conditions of the NASA Glenn AeroMACS prototype in Cleveland provided a DL throughput rate of at least 3 Mbps for a range of approximately 1.71 km for the following conditions:

- Clear line of sight from BS2 to ARV SS on runway 24L
- BTS sector transmit power: +21 dBm (125 mW) per MIMO channel
- BTS sector: 2 by 2 MIMO, mode A
- ARV SS: 2 by 1 MIMO, mode A
- BTS sector antenna gain: +16 dBi
- ARV SS antenna gain: +8 dBi

This test has established that a reasonable traffic throughput and range can be established with 125-mW BTS transmitter power under benign link conditions. Additional tests and analysis need to be completed to assure that this power level supports links into areas of higher signal multipath and NLOS conditions.

7.0   Conclusion

The ICAO approved concept for a broadband wireless mobile communications network to enhance safety and regularity of flight based on the IEEE 802.16 standard is being realized through AeroMACS. An international standard is being pursued through collaboration between RTCA in the U.S. and EUROCAE in Europe. A wide variety of mobile and fixed applications are envisioned as candidates for AeroMACS in the U.S. The FAA, NASA Glenn and ITT have developed the world's first AeroMACS prototype in Cleveland, Ohio. Experimental measurements and mobility performance data from the prototype are being use to validate parameters of the WiMAX profile for AeroMACS. Further research and experimentation via the prototype and AeroMACS-equipped research aircraft will enable recommendations on total AeroMACS radiated power limits to avoid interference with collocated services, and potential performance and operational improvements from the use of MIMO antenna configurations. AeroMACS is the first component of the FCI expected to realize the ANC-11 vision for global harmonization of A/G communications.

Appendix—Acronym List

4D-TRAD	four-dimensional trajectory negotiations
A/G	air to ground
AAA	authentication, authorization, and accounting
AAC	airline administrative communication
ACARS	Aircraft Communications Addressing and Reporting System
ACP	Aeronautical Communications Panel
AeroMACS	Aeronautical Mobile Airport Communications System
AIS	aeronautical information services
AM(R)S	aeronautical mobile (route) service
AMS	aeronautical mobile service
AMT	aeronautical mobile telemetry
ANC	Air Navigation Conference
AOC	aeronautical (airline) operational control
AP–17	Action Plan 17
ARFF	Aircraft Rescue and Firefighting
ARNS	Aeronautical Radio Navigation Services
ARV	Aeronautical Research Vehicle
ASDE-X	airport surface detection equipment model X
ASN	access services network
ASR	airport surveillance radar
ATC	air traffic control
ATCT	air traffic control tower
ATM	air traffic management
BS	base station
BTS	base transceiver station
CAASD	Center for Advanced Aviation System Development
CLE	Cleveland Hopkins International Airport
CNS	communication, navigation, surveillance
COCR	communications operating concepts and requirements
CPDLC	controller pilot data link communications
CSN	connectivity services network
D-AUS	data link aeronautical update services
DFW	Dallas Ft. Worth
DL	downlink
D-OTIS	airport/runway configuration information
D-SIG	surface information guidance
EFB	electronic flight bag
EUROCONTROL	European Organisation for the Safety of Air Navigation
FAA	Federal Aviation Administration
FCI	future communications infrastructure

FCS	Future Communications Study
FDD	frequency division duplex
FMS	flight management system
FOQA	flight operational quality assurance
FRS	future radio system
GPS	global positioning satellite
GSO	geostationary orbiting
GTG	graphical turbulence guidance
HF	high fidelity
ICAO	International Civil Aviation Organization
IEEE	Institute of Electrical and Electronics Engineers, Inc,
IP	Internet protocol
LOS	line of sight
MET	meteorological
MIMO	multiple-input, multiple-output
MLAT	multilateration
MLS	microwave landing system
MOPS	minimum operational performance standards
MSS	mobile satellite service
NAS	National Airspace System
NextGen	Next Generation Air Transportation System
NLOS	non line of site
NMS	network management system
ODU	outdoor unit
OFDMA	orthogonal frequency division multiple access
PDC	pre-departure clearance
PDP	power delay profile
PHY	physical layer
QoS	quality of service
RFID	radiofrequency identification
RMM	remote maintenance and monitoring
RSS	received signal strength
RSSI	receive signal strength indication
RTR	remote transmit receiver
SESAR	Single European Sky ATM Research
SF	sufficient fidelity
SS	subscriber station
SWIM	System Wide Information Management
TDD	time division duplex
TRACON	terminal radar approach control
UL	uplink

VHF	very high frequency
VLAN	virtual local area networks
VoIP	voice over Internet protocol
WAAS	wide area augmentation system
WGT	Working Group Technology
WGW	Working Group of the Whole
WiMAX	Wireless Worldwide Interoperability for Microwave Access

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14. ABSTRACT
To help increase the capacity and efficiency of the nation's airports, a secure wideband wireless communications system is proposed for use on the airport surface. This paper provides an overview of the research and development process for the Aeronautical Mobile Airport Communications System (AeroMACS). AeroMACS is based on a specific commercial profile of the Institute of Electrical and Electronics Engineers (IEEE) 802.16 standard known as Wireless Worldwide Interoperability for Microwave Access or WiMAX (WiMax Forum). The paper includes background on the need for global interoperability in air/ground data communications, describes potential AeroMACS applications, addresses allocated frequency spectrum constraints, summarizes the international standardization process, and provides findings and recommendations from the world's first AeroMACS prototype implemented in Cleveland, Ohio, USA.

15. SUBJECT TERMS
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